Cold nuclear matter effects in J/ψ production in p-nucleus collisions

- Energy and rapidity dependence of σ_{abs}(J/ψ)
- Initial state parton energy loss
- J/ψ feed-down fractions from χ_c and ψ' decays

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Nuclear effects in quarkonium production in p-A collisions

Several "cold nuclear matter effects" can modify the production of quarkonia in p-nucleus collisions with respect to pp collisions. In particular, we expect:

initial-state effects:

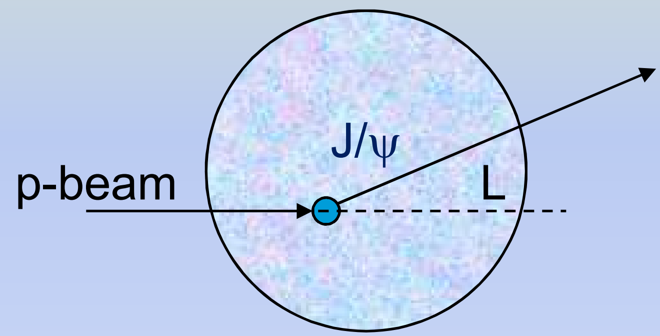
- nuclear modifications to the PDFs
- initial-state energy loss of incident partons

final-state effects:

- break-up of formed or pre-resonant charmonia (different for each charmonium state)

absorption

$\sim \exp\{-\rho\, L\, \sigma_{abs}\}$



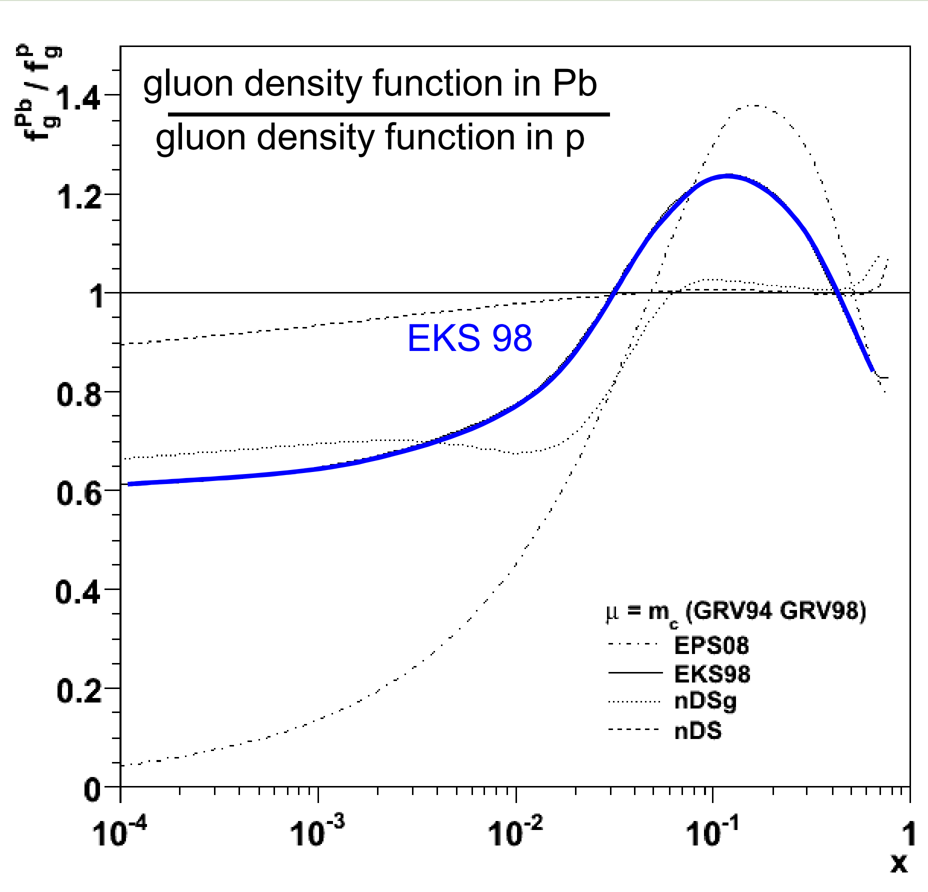
To understand these effects we need to study several data sets, collected in different kinematical domains, at different energies, with several nuclear targets, etc.

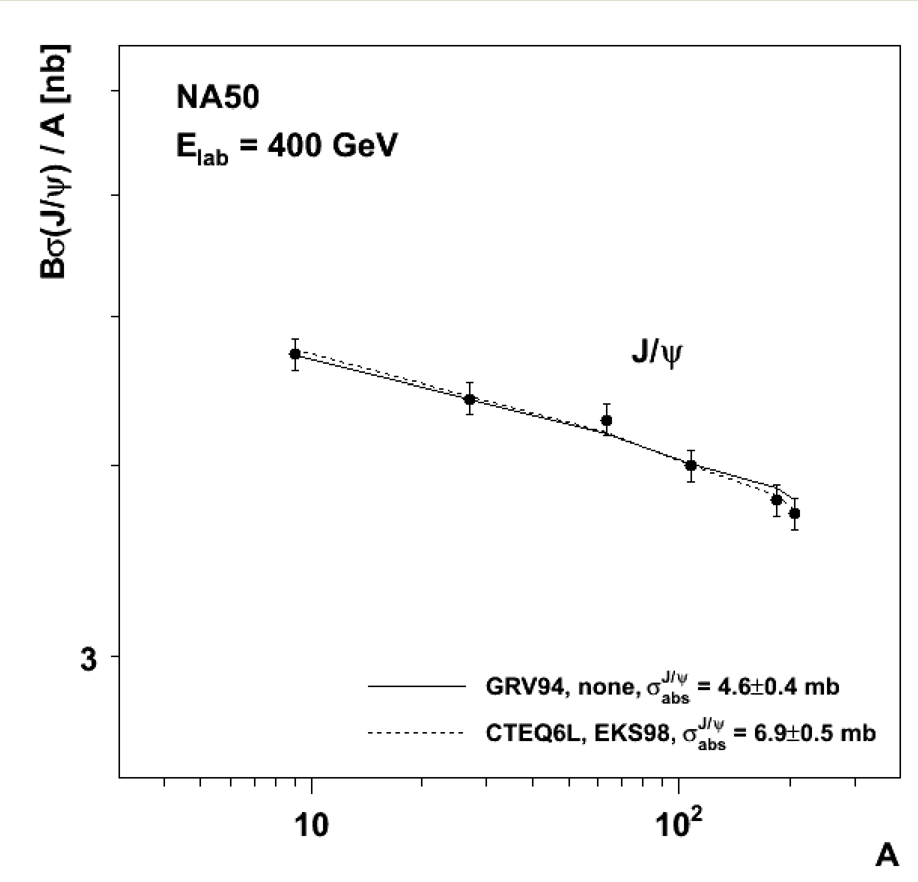
And we need to consider the ψ' and χ_c measurements, together with the J/ψ results; around 1/3 of the J/ψ yield is due to decays of ψ' and χ_c mesons

Nuclear effects on the Parton Distribution Functions

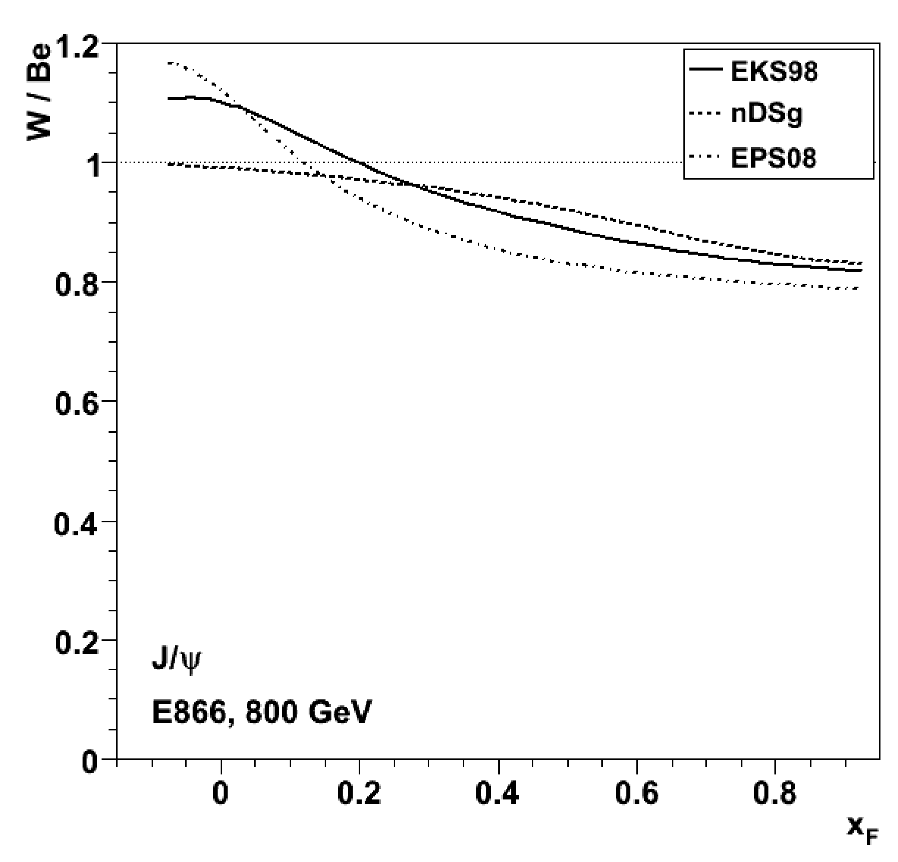
At x values ~ 0.1–0.4 (SPS), there is gluon *anti-shadowing* (EKS98); the J/ψ prod. cross section per nucleon *increases* from pp to p-Pb (before final state absorption)

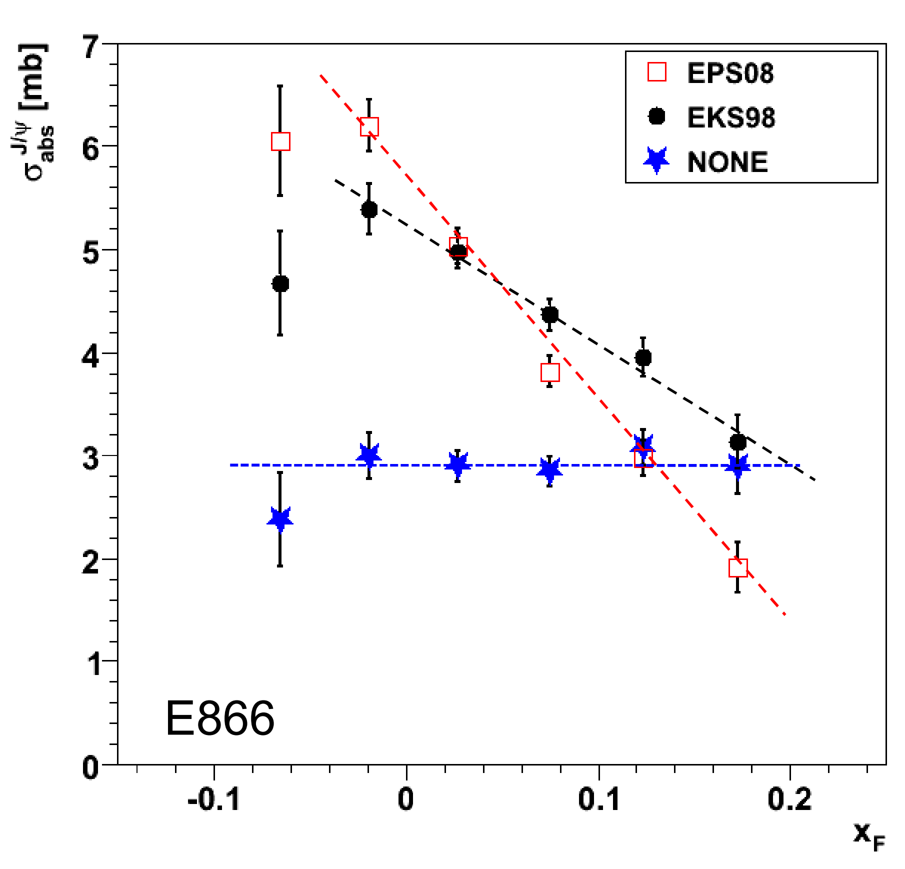
⇒ The NA50 measurements are equally well described using σ_{abs} = 6.9 mb (with EKS98) or σ_{abs} = 4.6 mb (with "free protons")





J/ψ σ_{abs} versus x_F : the importance of the N-PDFs





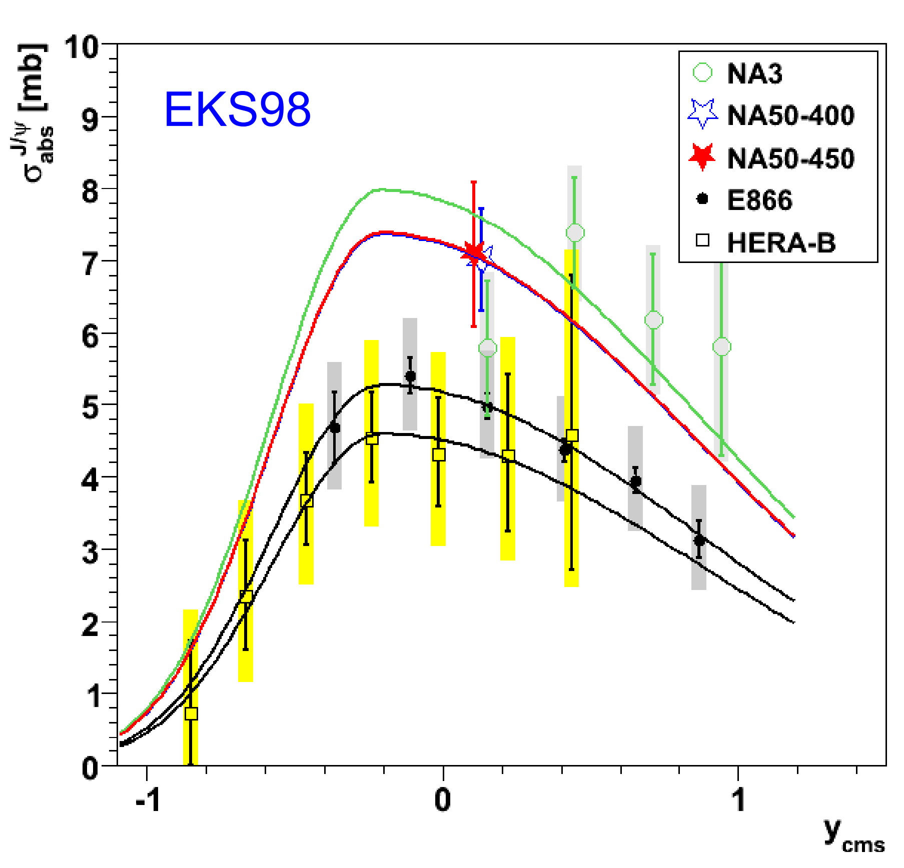
- The nuclear effects on the PDFs are a function of Bjorken-x
  $\Rightarrow$ energy *and* x_F (or rapidity) dependent
- At $x_F < 0.2$: strong anti-shadowing in EKS98 and EPS08 :
  $\Rightarrow$ In the absence of other effects, the E866 W/Be ratio should be higher than unity
- The nuclear modifications of the PDFs significantly change the x_F dependence of σ_{abs}

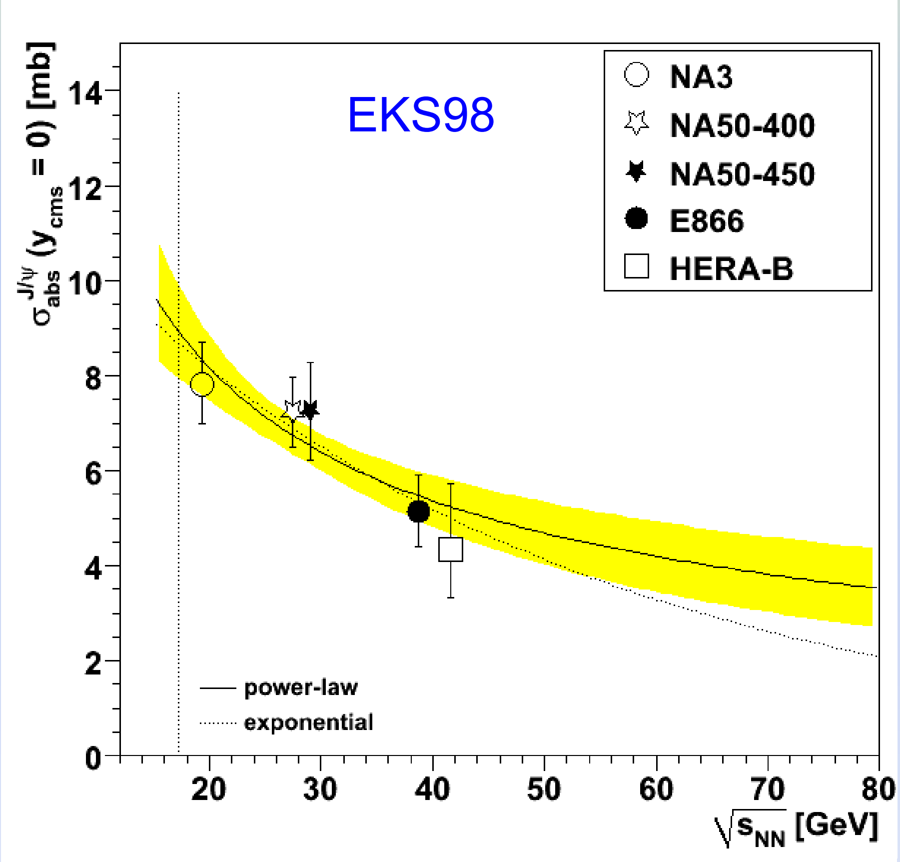
J/ψ σ_{abs} versus rapidity and collision energy

The nuclear dependence of the J/ψ production cross section was studied by several experiments, probing different collision energies and J/ψ kinematics

The E866 and HERA-B patterns define the *shape* of the rapidity dependence of σ_{abs}

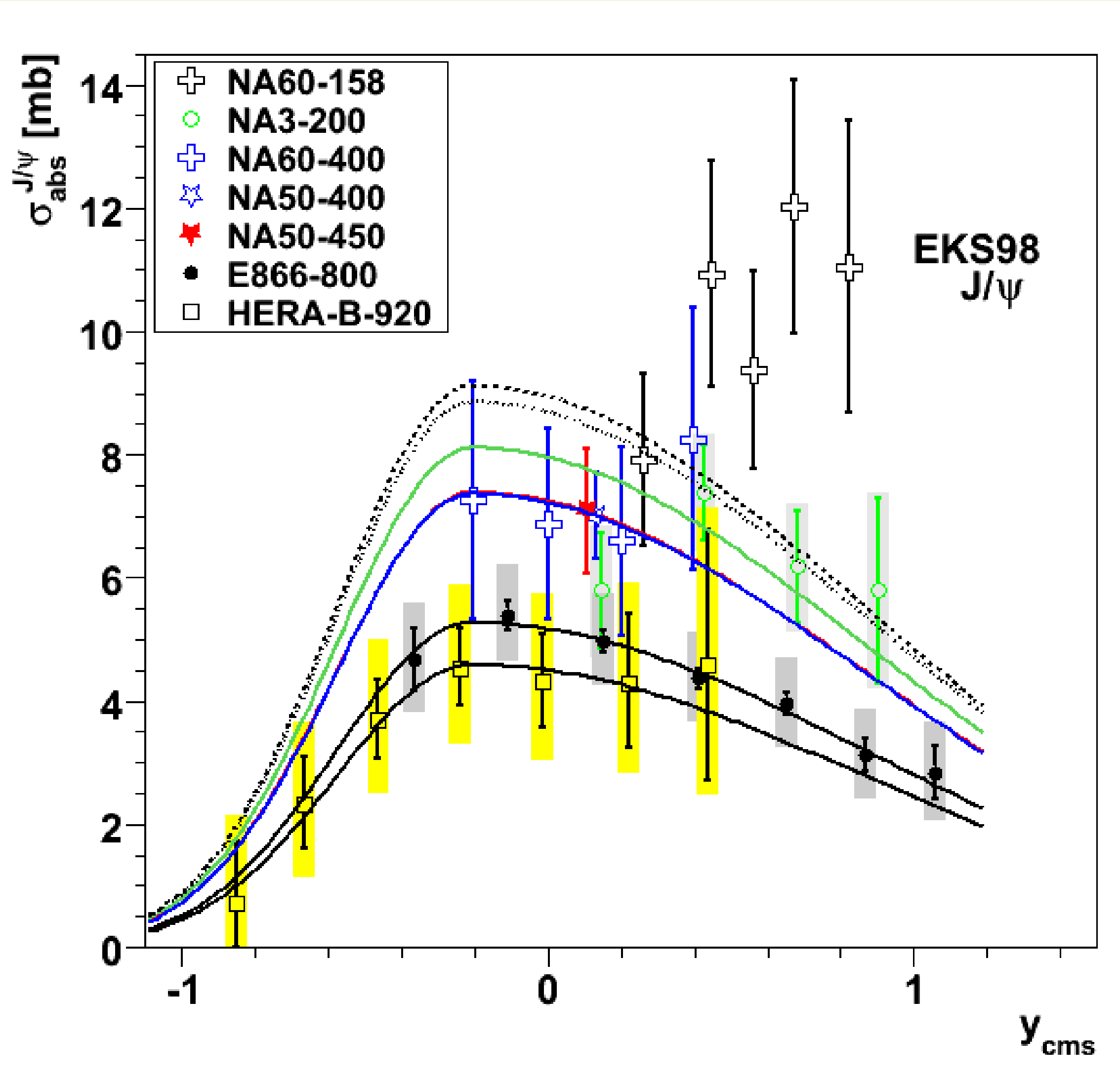
σ_{abs} at y_{cms}=0 decreases with NN collision energy





What can we learn from the new NA60 data?

NA60 collected p-A data at 400 and 158 GeV with 7 targets: Be, Al, Cu, In, W, Pb and U



Extrapolation to y_{CMS}=0 at 158 GeV gives a σ_{abs} of:
9.0±0.9 mb with power-law
8.7±0.6 mb with exponential

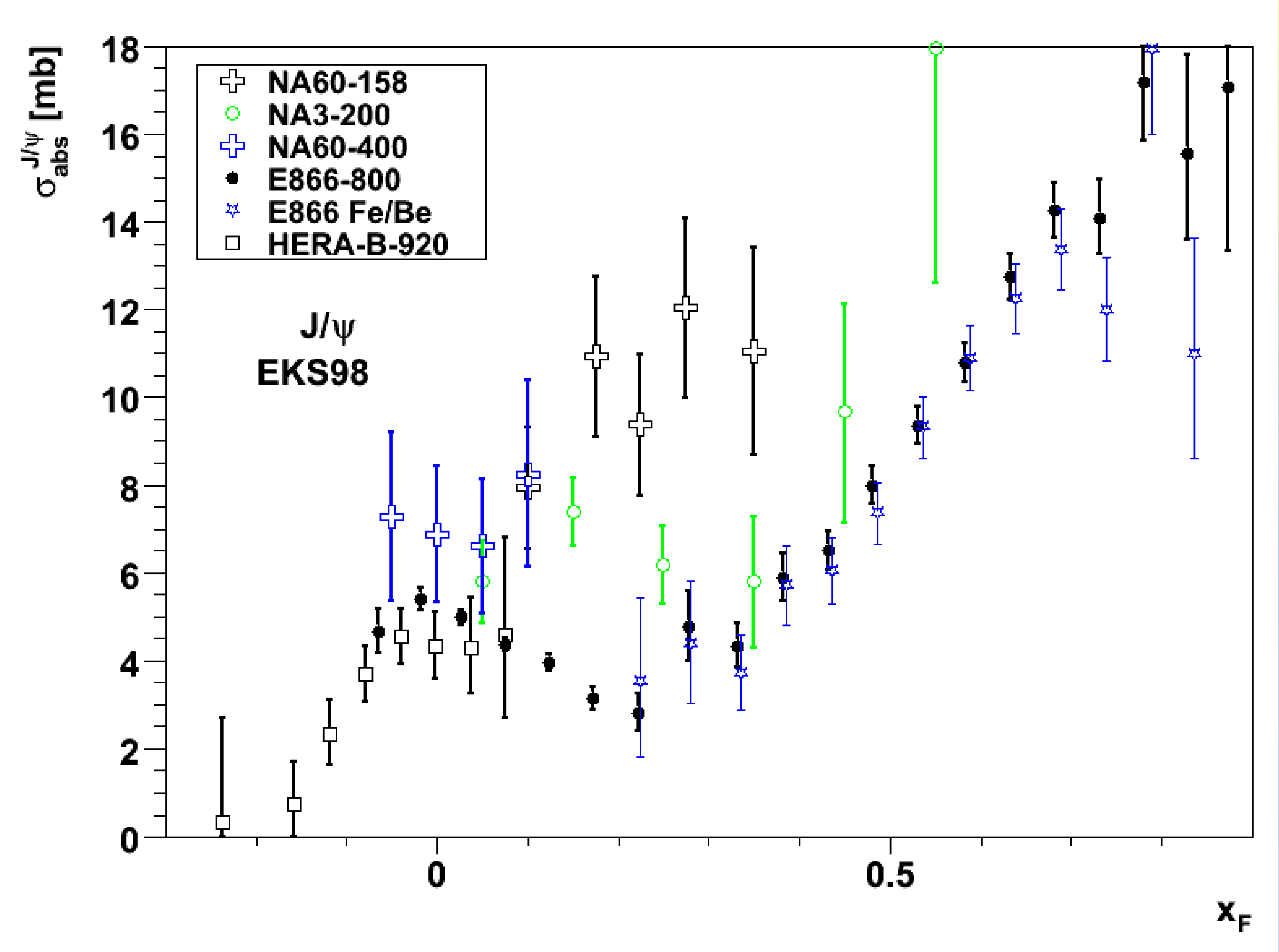
Let's compare to the new NA60 data, shown at QM09

The 400 GeV data points are perfectly compatible with the previously established trend

The first 158 GeV point sits on the expected curve but the others are much higher

Do we see a departure from the absorption pattern? What about other nuclear matter effects?

The forward x_F region is visibly different



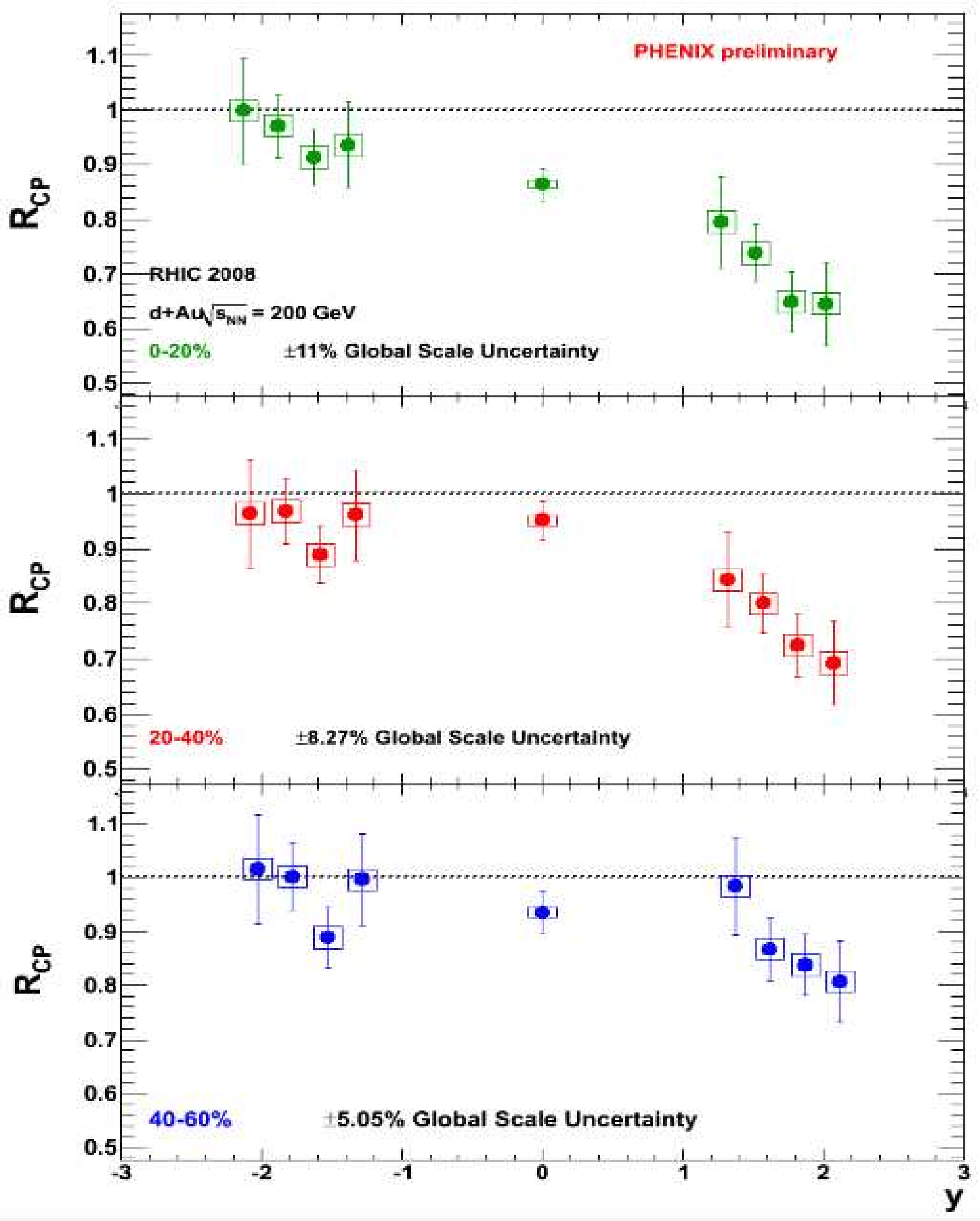
E866 shows that at forward x_F other effects play a role

NA3 also shows much larger σ_{abs} at forward x_F

NA60-400 (at x_F~0) is compatible with absorption only…

while the (forward) 158 GeV data seem to follow the E866 trend

What can we learn from the PHENIX data?

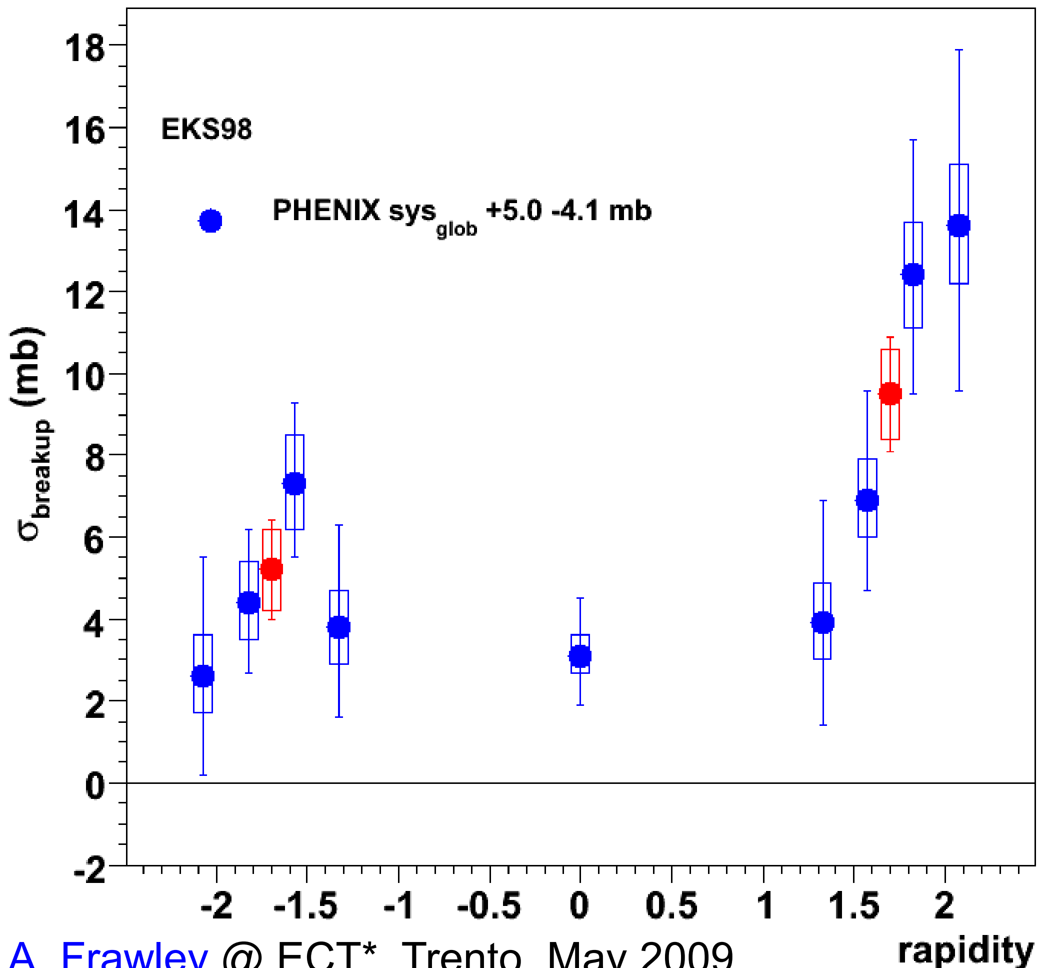


At QM09 three R_{CP} values were shown from the d-Au data of Run-8:

$$R_{CP} = \frac{\frac{dN}{dy}[0-20, 20-40, 40-60\%]}{\frac{dN}{dy}[60-88\%]}$$

From a combined fit to the three R_{CP} values, one σ_{abs} value was extracted for each bin in rapidity.

Rapidity differential σ_{abs} from PHENIX



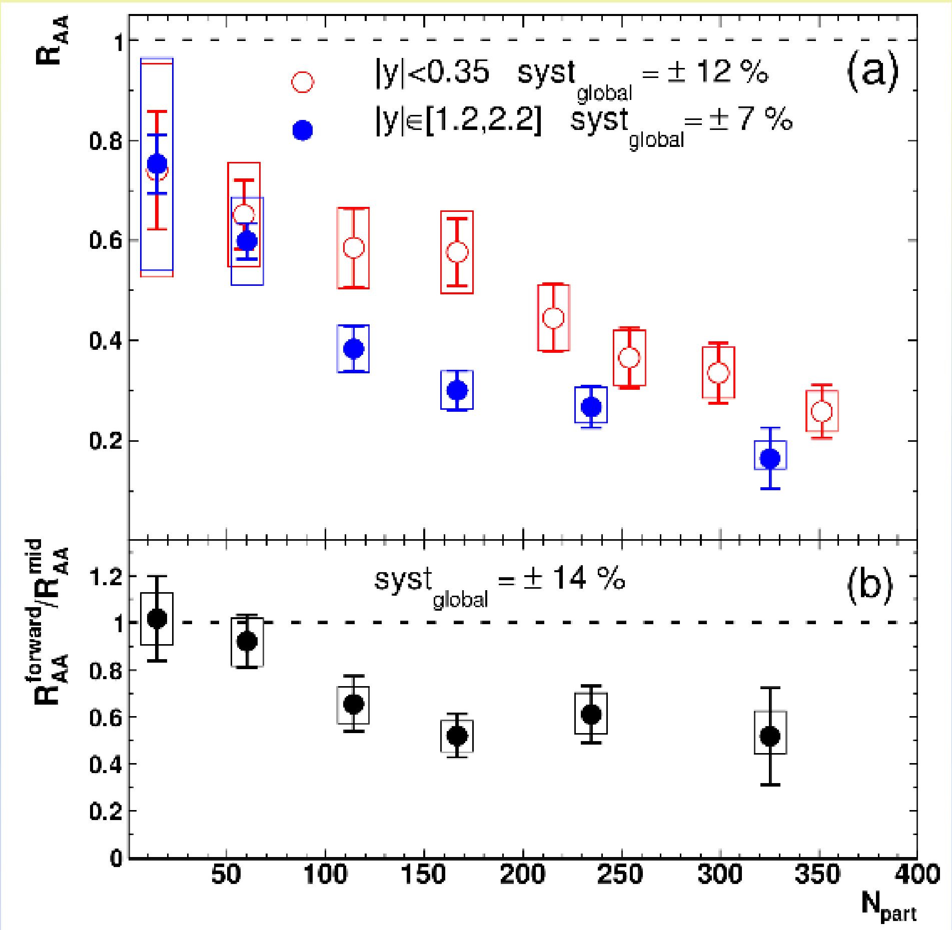
A. Frawley @ ECT*, Trento, May 2009

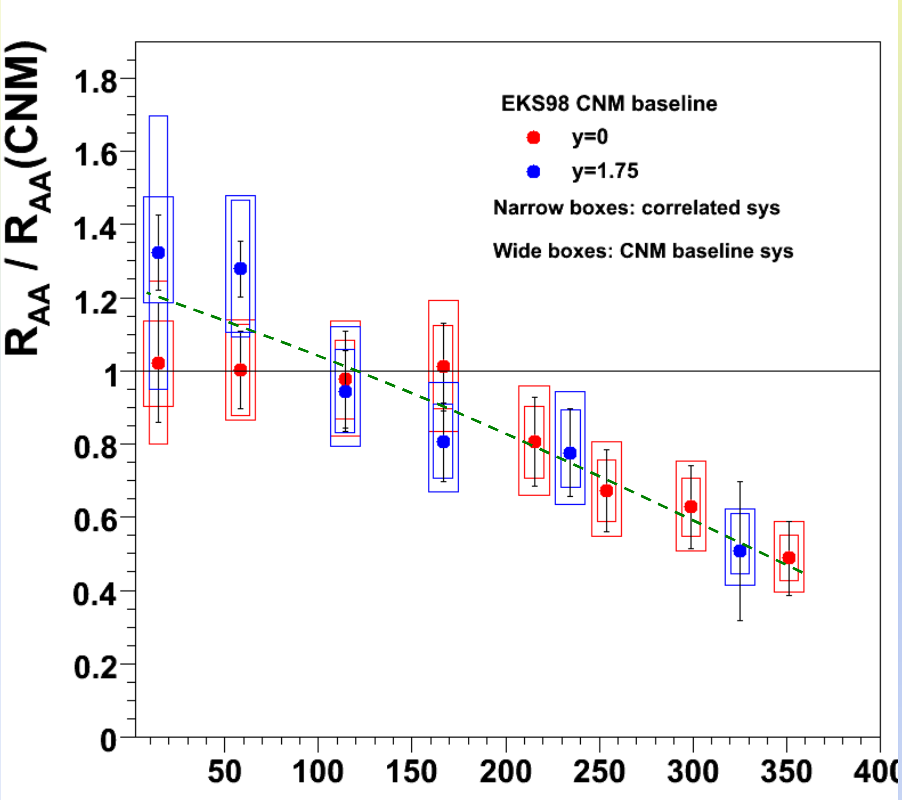
Also the PHENIX measurements show that σ_{abs} depends on rapidity.

A future analysis of d-Au / pp ratios, instead of R_{CP}, should provide smaller errors.

The red points are the σ_{abs} values integrated in the backward and forward rapidity windows. They define the reference baseline used when looking at the Au-Au data.

New baseline for Au-Au





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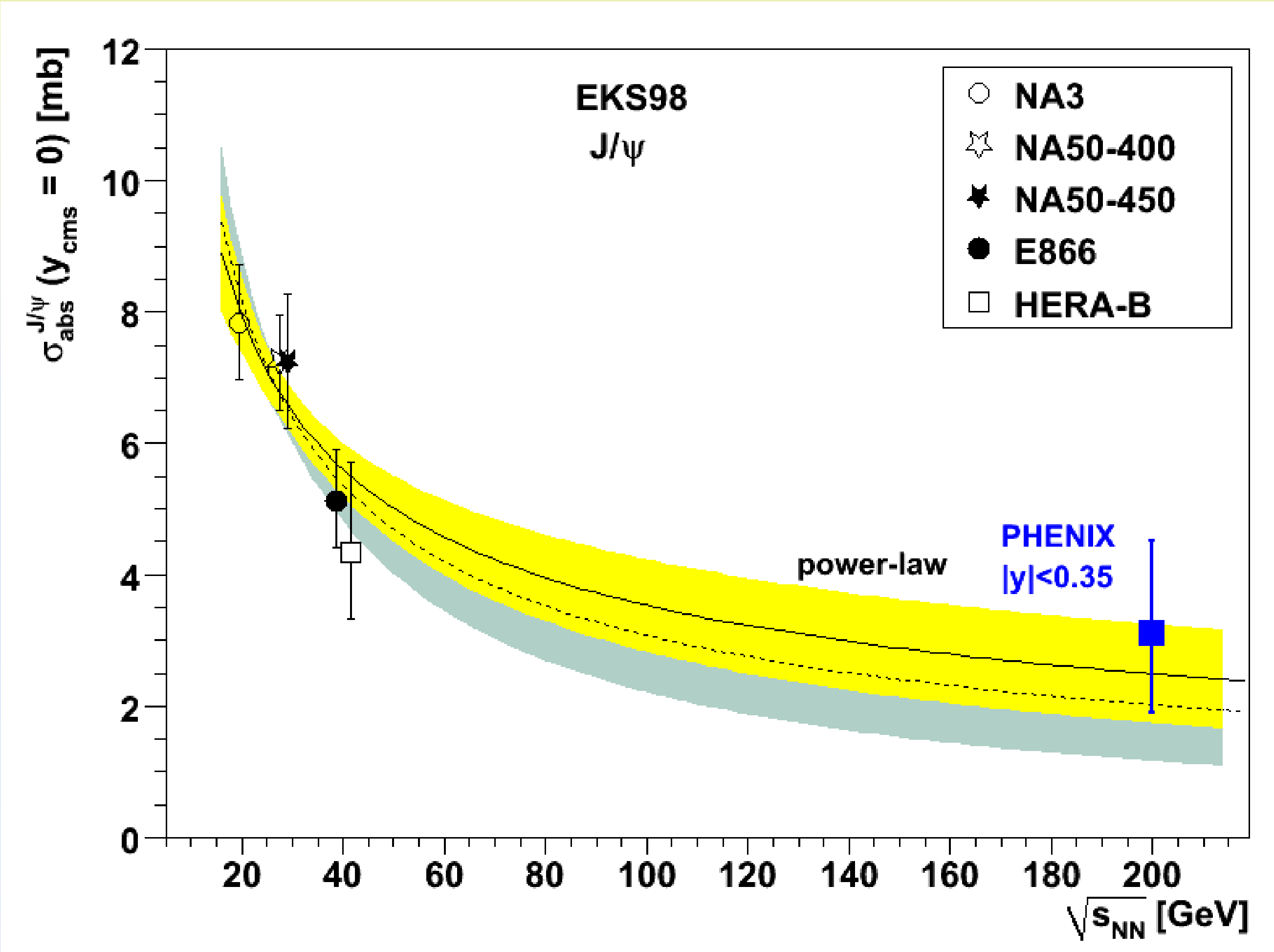
The puzzling stronger suppression of the forward Au-Au data disappears if we account for the rapidity dependence of σ_{abs}.

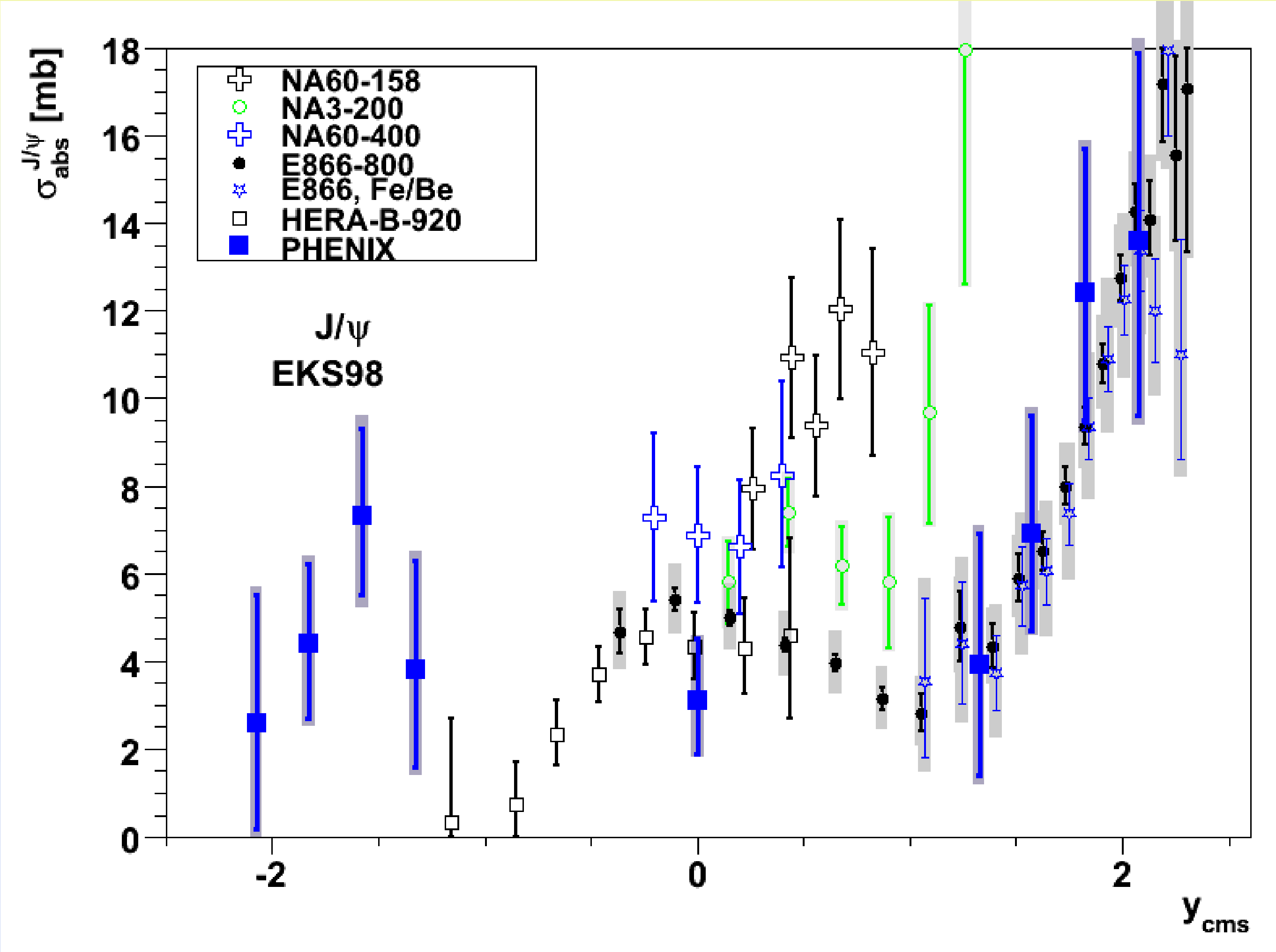
Puzzles often disappear when references are improved…

σ_{abs} from PHENIX vs. other mid-rapidity values



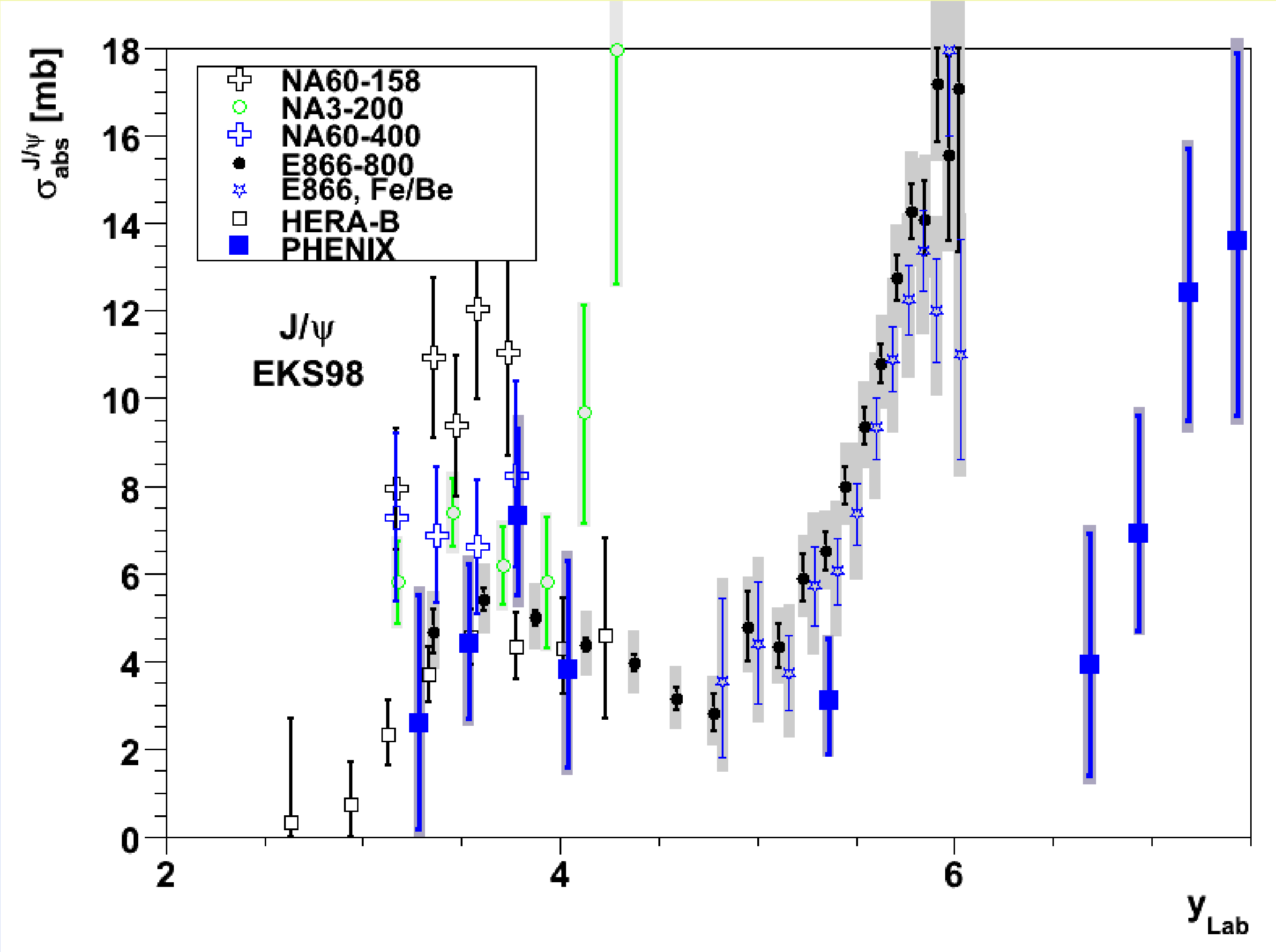
The mid-rapidity σ_{abs} value follows the extrapolation from the low energy data.

Global comparison of all data sets vs. y_{cms}



The broad rapidity coverage of the PHENIX data should considerably help in discriminating the different cold nuclear matter effects, by comparing data sets as a function of several kinematical variables

Global comparison of all data sets vs. y_{lab}



Different effects should depend on different kinematical variables

The PHENIX errors will improve in the near future (using the R_{dAu} ratio)

A first and simple look at parton energy loss (work in progress)

The beam partons may lose energy traversing the nucleus, before J/ψ creation. For now, we model this effect in a very simple way, assuming a constant relative loss of energy in each of the "collisions" taking place before the one where the quarkonium is produced: $E_g' = E_g\,(1-\varepsilon_g)^{(N_{coll}-1)}$

The energy loss per NN collision is different for gluons and quarks: ε_g and ε_q

We start by assuming that $\varepsilon_q = 4/9\ \varepsilon_g$ but then we release this condition

The decreased energy leads to changes in the calculated x_F J/ψ distribution

$$\sigma_{p-A} = \sum_{ij=gg,q\bar{q}} \int \int_{m=2m_Q}^{2m_D} dm\ dx_1 dx_2 f_i^p\left(x_1,Q^2\right)\cdot f_j^A\left(x_2,Q^2\right)\cdot \sigma_{ij}(x_1',x_2,m^2,s)$$

Smaller than in the pp case

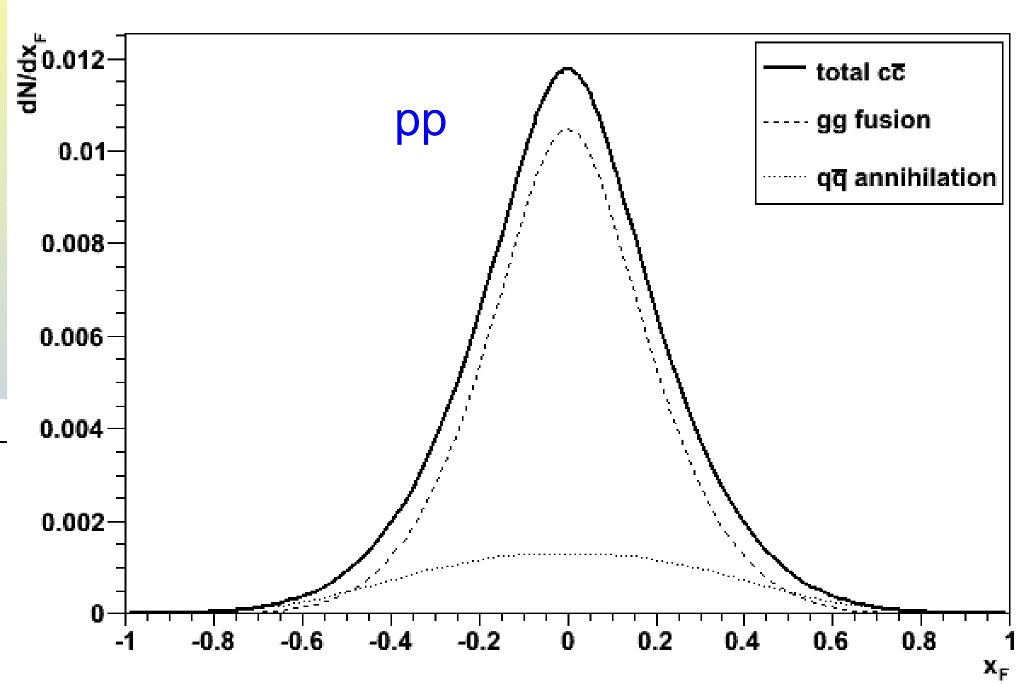
Note: the average number of NN collisions is obtained with the Glauber model

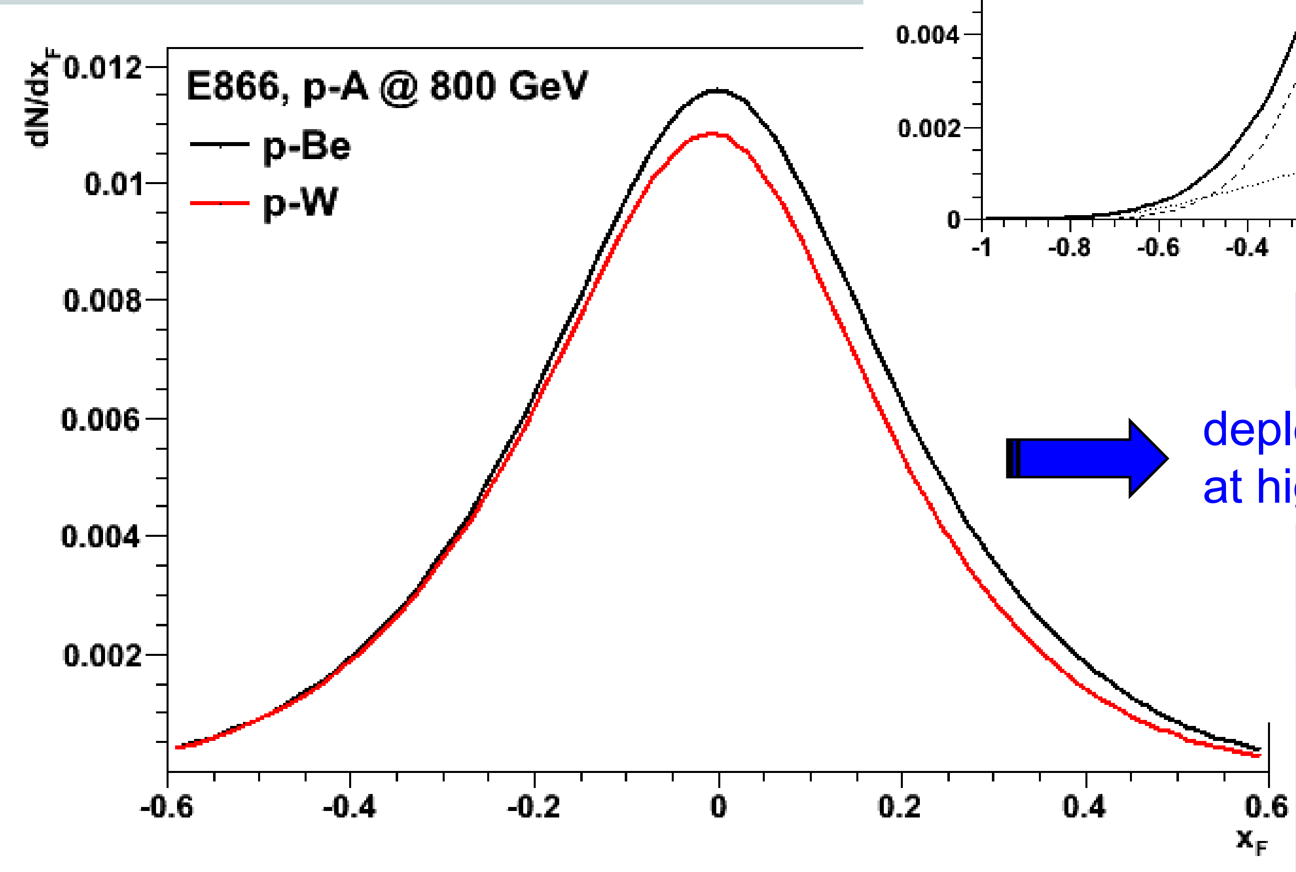
Effect of parton energy loss in the x_F distribution

The p-A x_F distributions are shifted to the backward hemisphere:

$$x_F' = x_1' - x_2 < x_F$$

and the production yield decreases



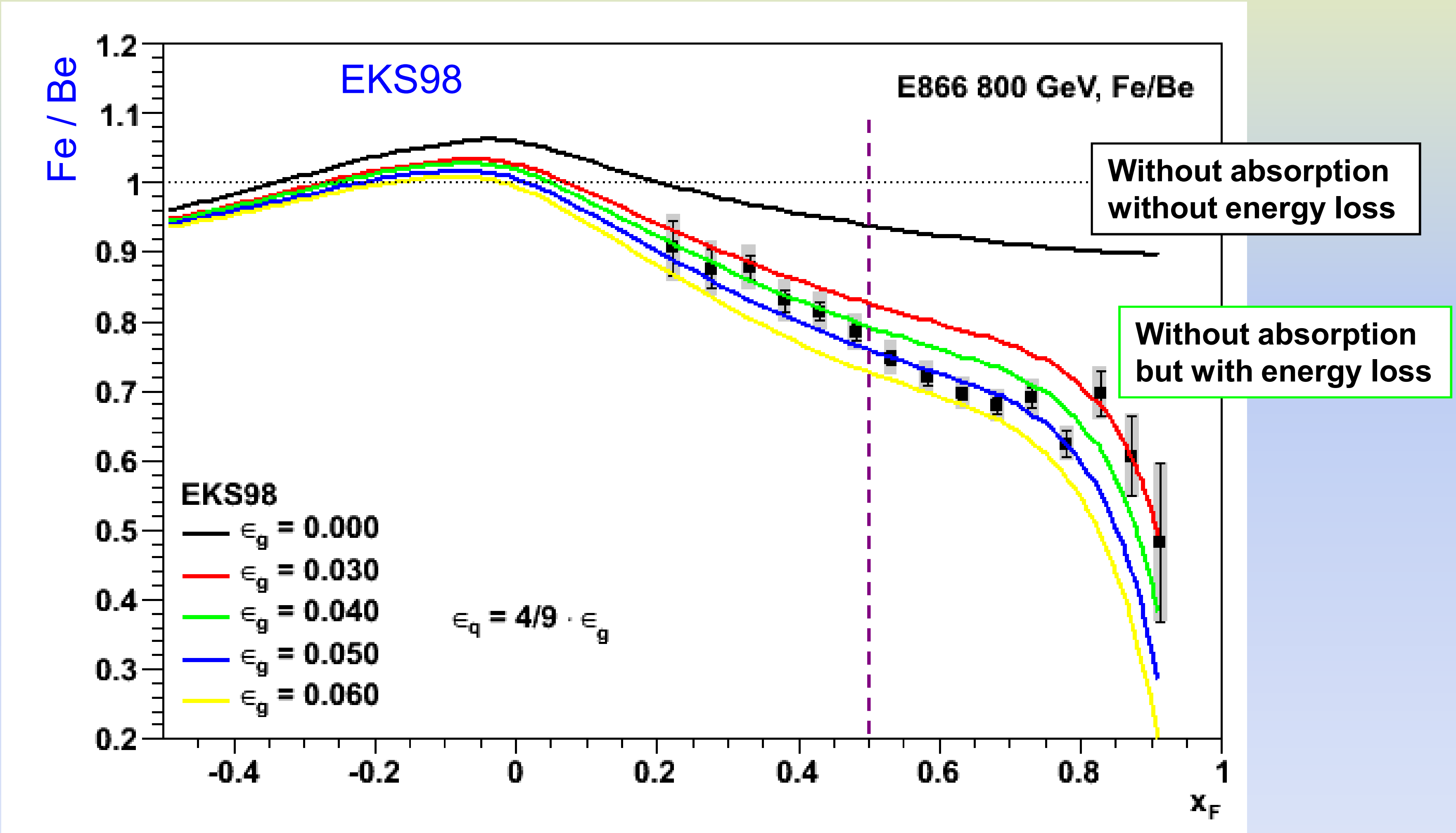


depletion of J/ψ production at high x_F in p-A collisions

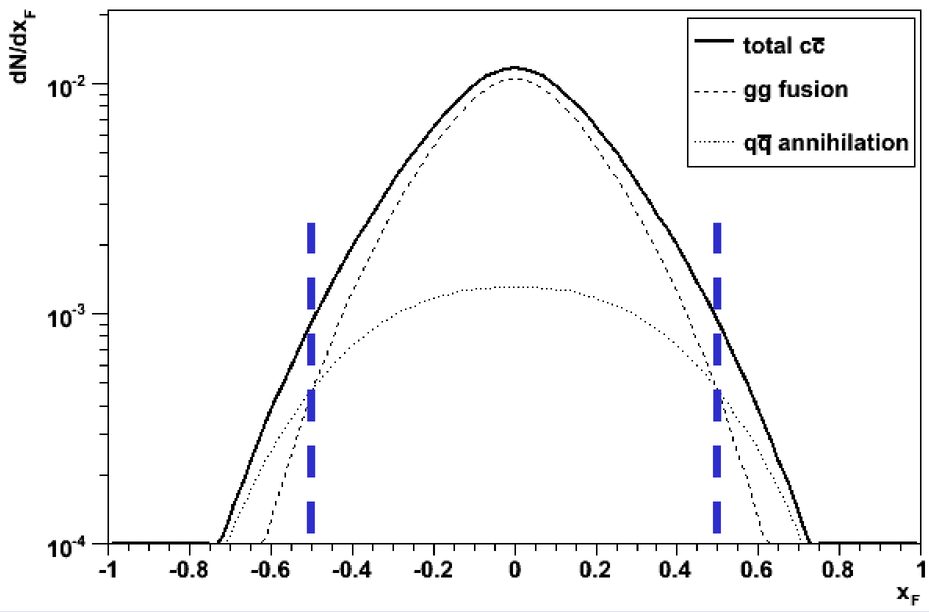
E866, 800 GeV, W / Be and Fe / Be ratios

ε_g = 4% and $\varepsilon_q = 4/9\ \varepsilon_g$ give a good description of the $0.2 < x_F < 0.5$ window

The more forward x_F region is not very well described…



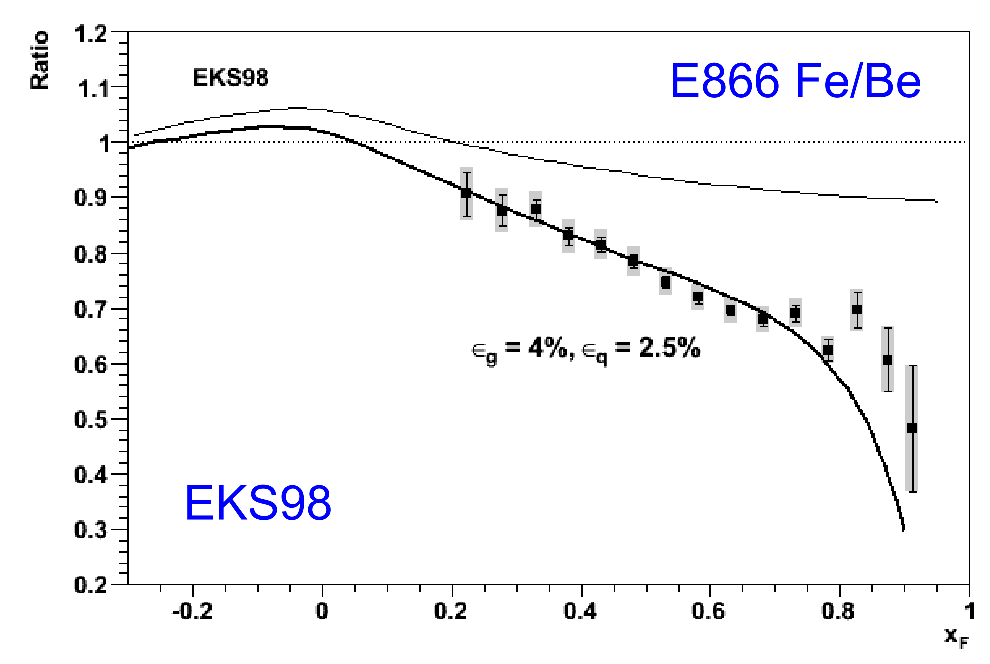
The very forward region



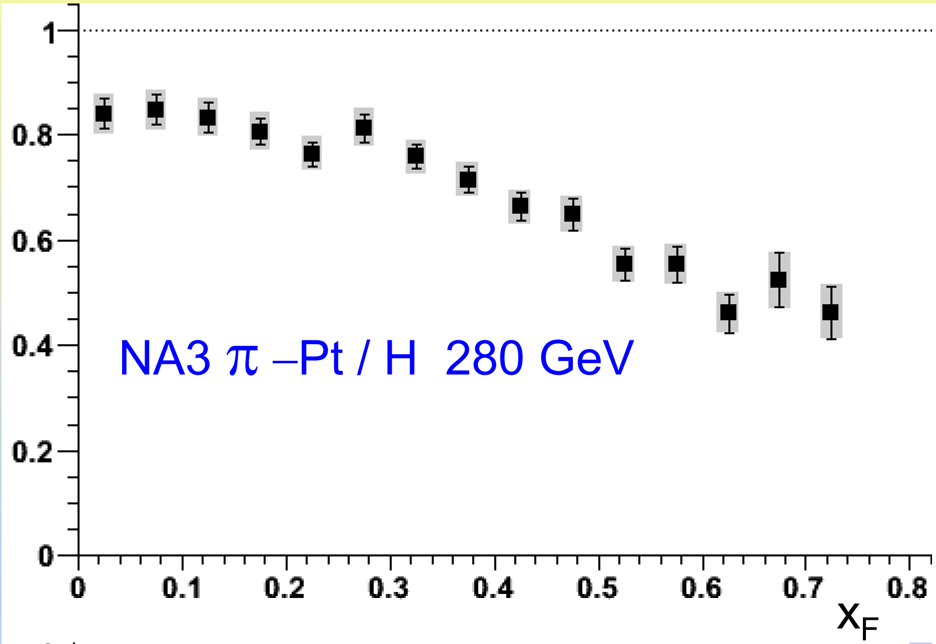
The $x_F > 0.5$ region is dominated by quark-antiquark annihilation

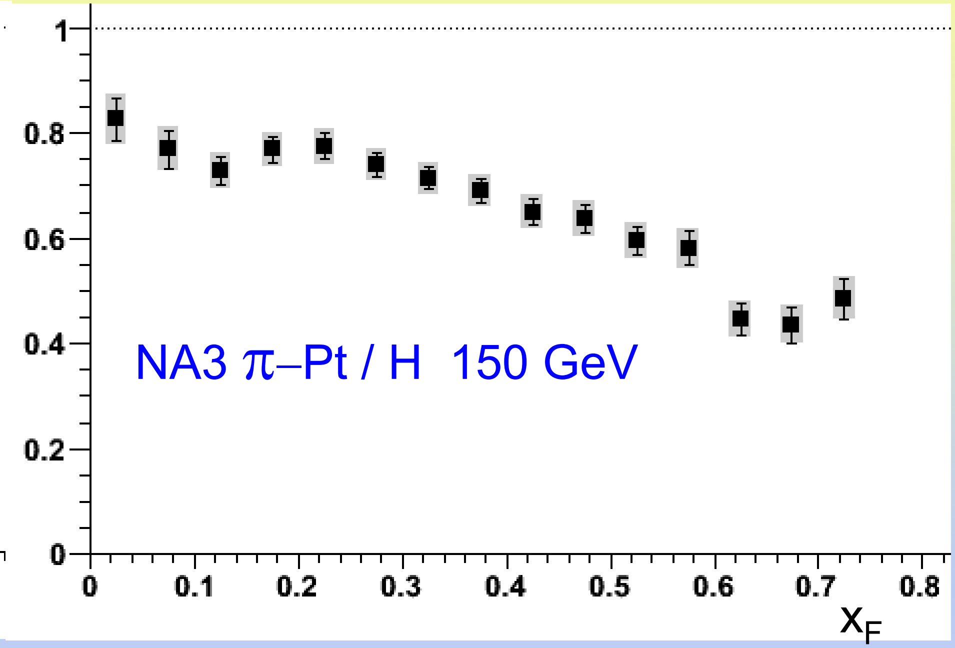
→ we can tune ε_q from that region

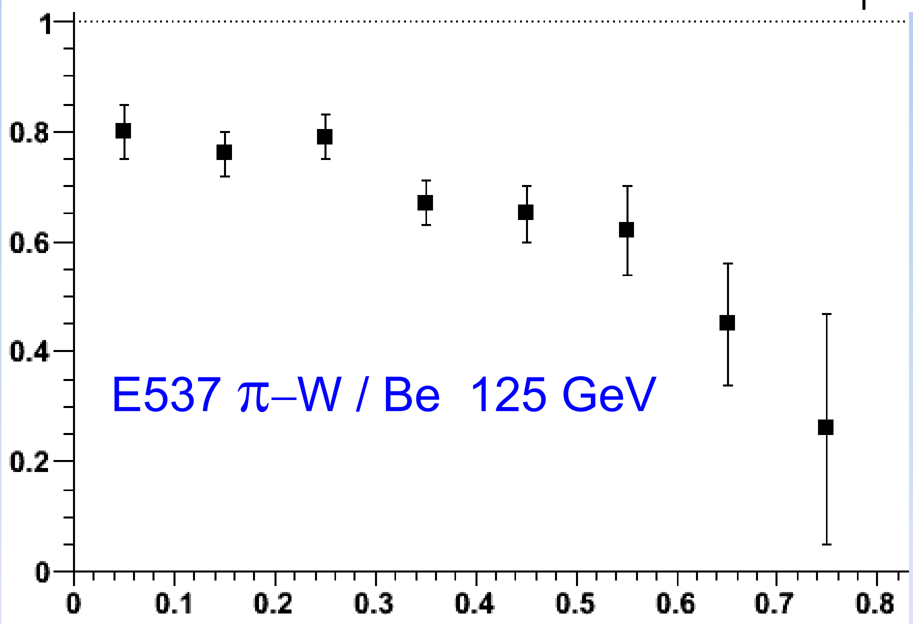
$\varepsilon_q = 2.5\%$ (instead of 1.8%) describes well the broad $0.2<x_F<0.7$ window



There are a few more p-A and π-A data sets







And others (NA60, PHENIX, etc), besides measurements on open charm and Drell-Yan dimuons

J/ψ feed-down contributions: from ψ' decays

The fraction of J/ψ events resulting from ψ' decays $R(\psi') = \dfrac{\text{J}/\psi\text{'s from } \psi'}{\textit{ALL}\ \text{J}/\psi\text{'s}}$

is obtained from the measurements of $\rho(\psi') = \dfrac{\sigma(\psi')\, B(\psi' \to \ell\ell)}{\sigma_{incl}(J/\psi)\, B(J/\psi \to \ell\ell)}$

The "pp" value $R^0(\psi')$ is obtained from the p-nucleus data assuming an exponential absorption model:

$$\left(\frac{\sigma^{\psi'}}{\sigma^{J/\psi}}\right)_{p-A} = \left(\frac{\sigma^{\psi'}}{\sigma^{J/\psi}}\right)_{pp} e^{-\Delta\sigma_{abs}\ \rho\ L(A)}$$

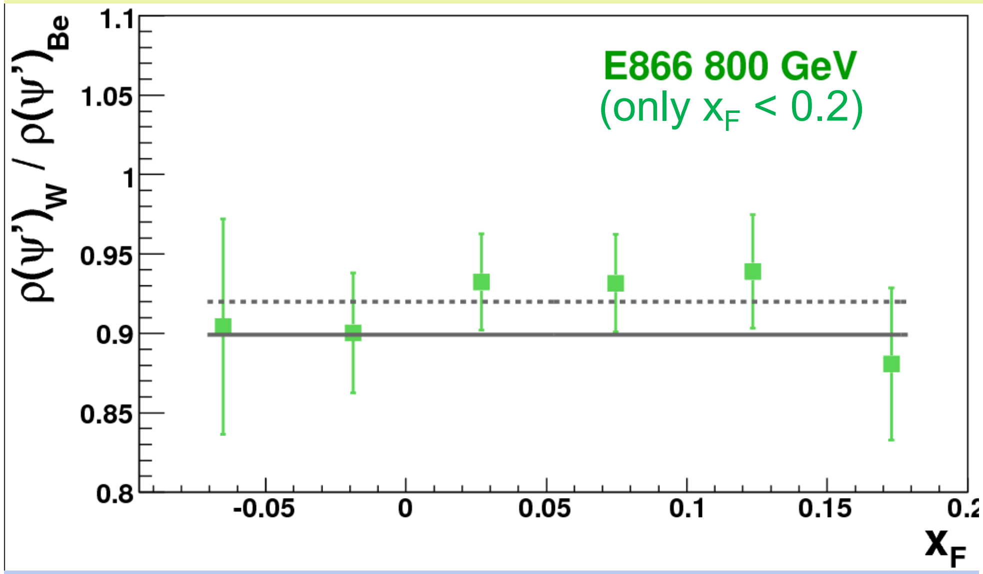
We define the difference of absorptions cross sections as $\Delta\sigma_{abs} = \sigma_{abs}(\psi') - \sigma_{abs}(J/\psi)$ where the J/ψ term does not include the ψ' contribution

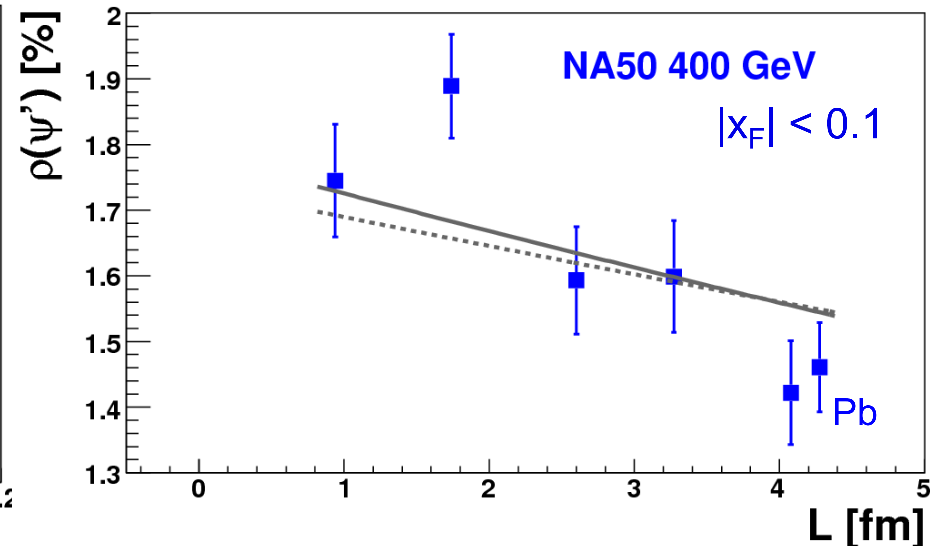
We extract $R^0(\psi')$ and $\Delta\sigma_{abs}$ from a global fit of two data sets:

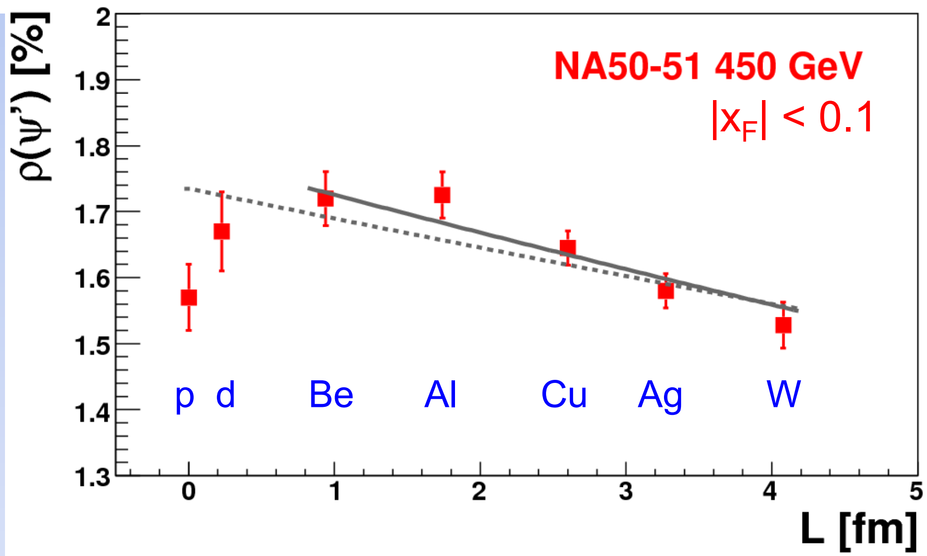
- NA50: production cross sections in 6 target nuclei, at 400 and 450 GeV
- E866: comparing p-W to p-Be, at 800 GeV

P. Faccioli C. Lourenço, J. Seixas and H.K. Wöhri, JHEP 10 (08) 4

J/ψ feed-down contributions: from ψ' decays



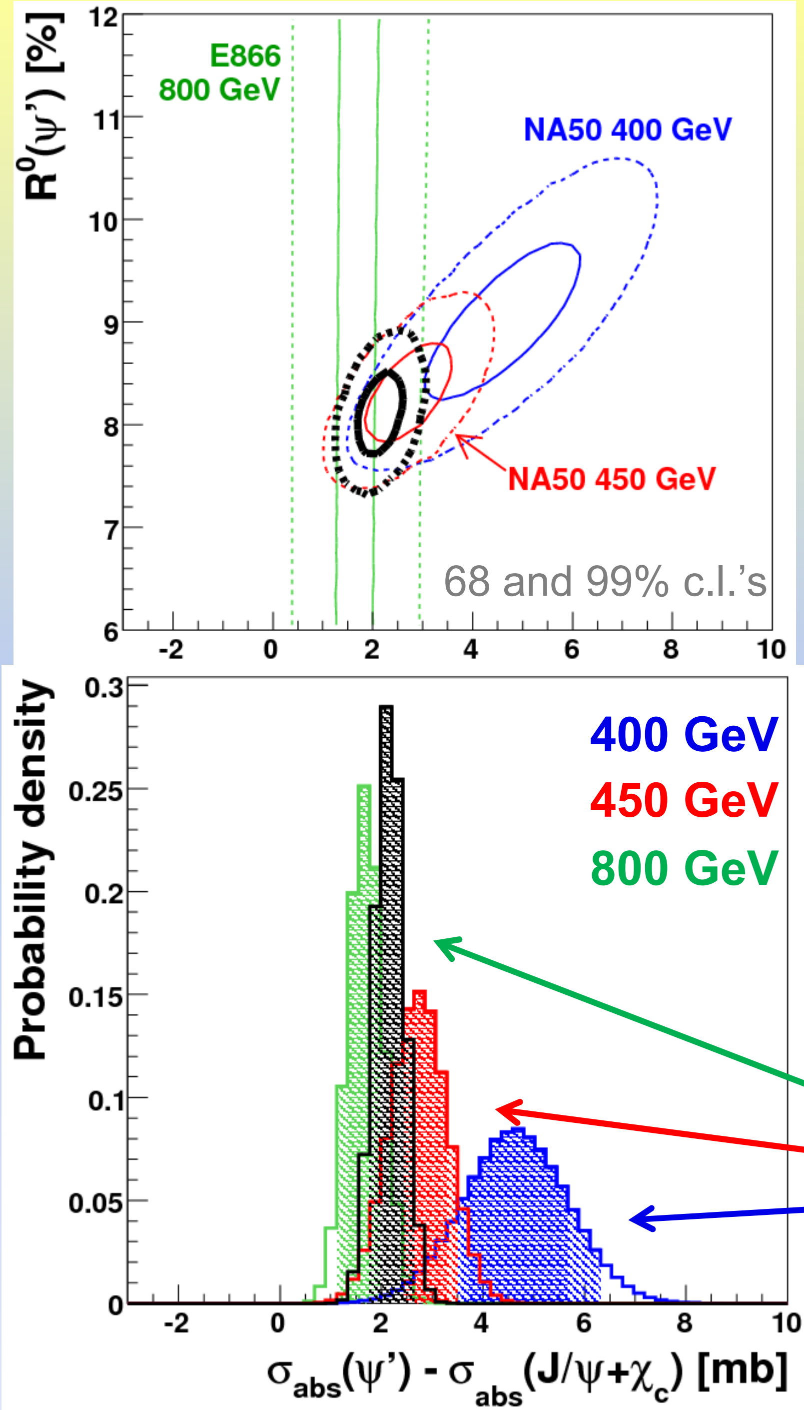




- The (Glauber) model used does not reproduce the H and D data points
- Are H and D nuclei not large enough to be traversed by fully formed states?

all data: $P(\chi^2) = 1\%$

without H and D data: $P(\chi^2) = 27\%$



NA50 400 GeV
NA50 450 GeV
E866 800 GeV

black: all combined
($\rightarrow$ global fits shown in the previous slide)

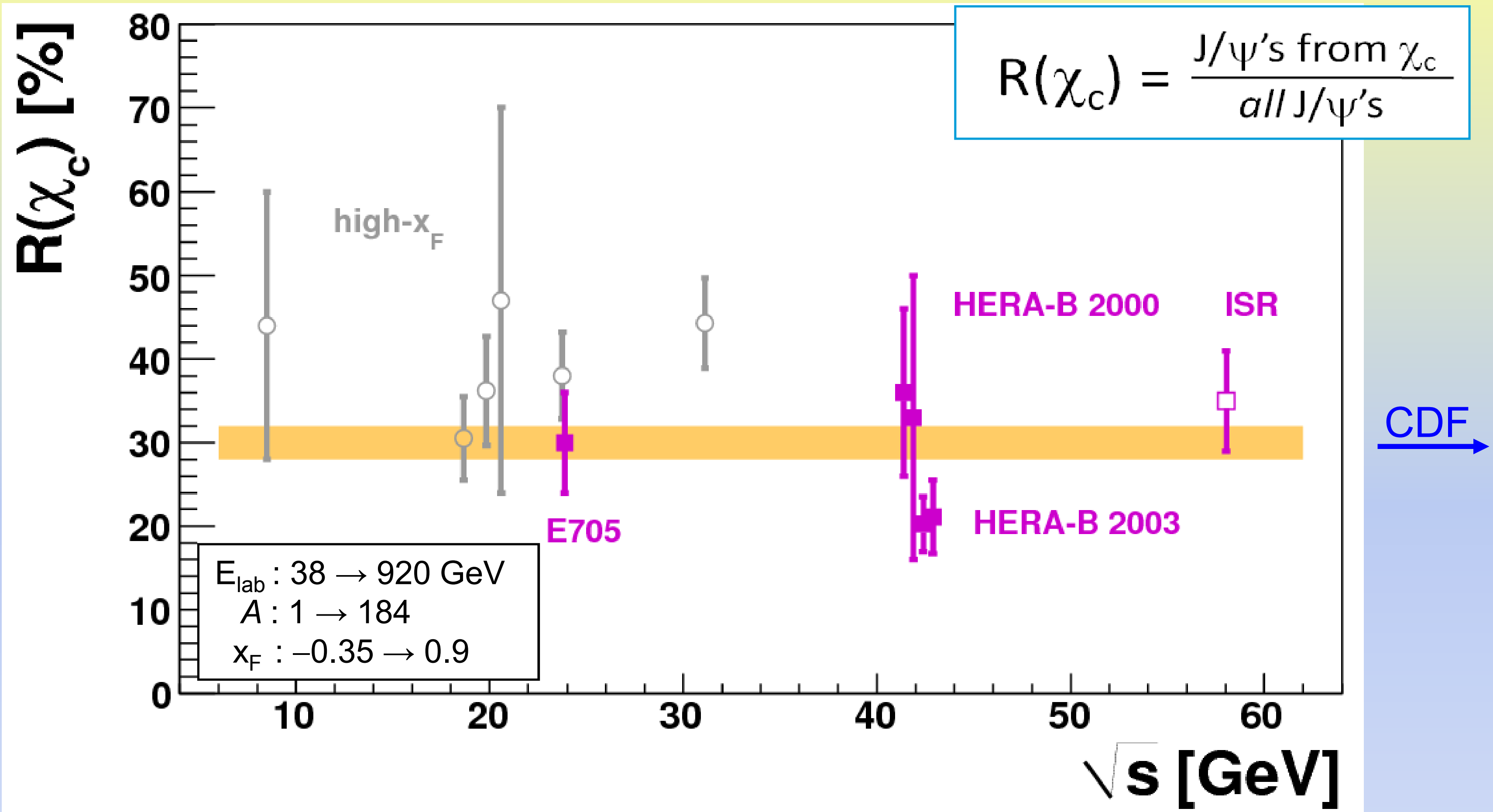
$R^0(\psi') = 8.1 \pm 0.3$ %
$\Delta\sigma_{abs} = 2.2 \pm 0.3$ mb

The error of $R^0(\psi')$ is dominated by uncertainties of branching fractions

The (preliminary) PHENIX pp value, measured at $\sqrt{s}$ = 200 GeV, is:
$R^0(\psi') = 8.6 \pm 2.5$ %

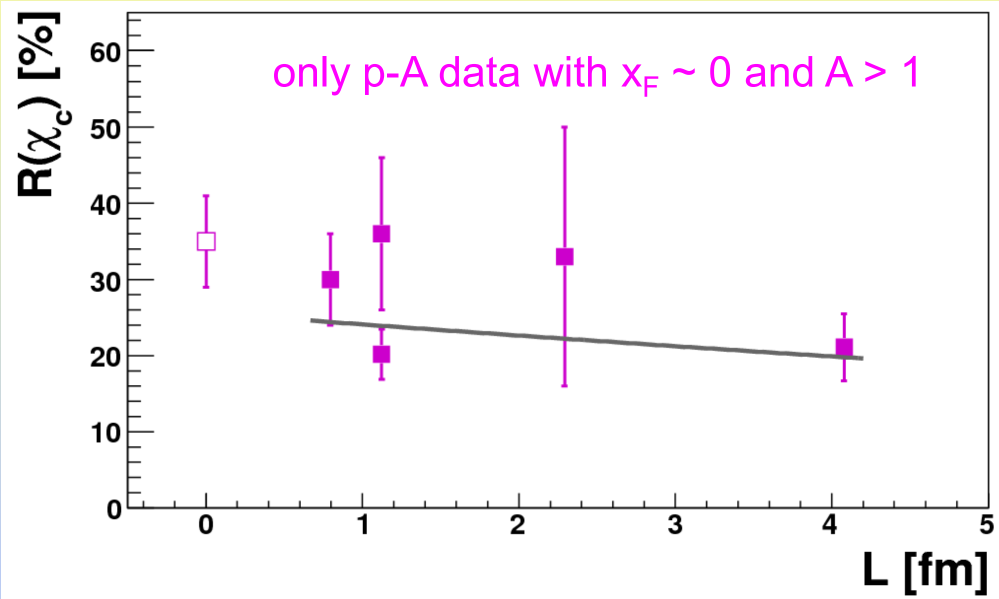
The three values are compatible but…
it seems that $\Delta\sigma_{abs}$ decreases with energy

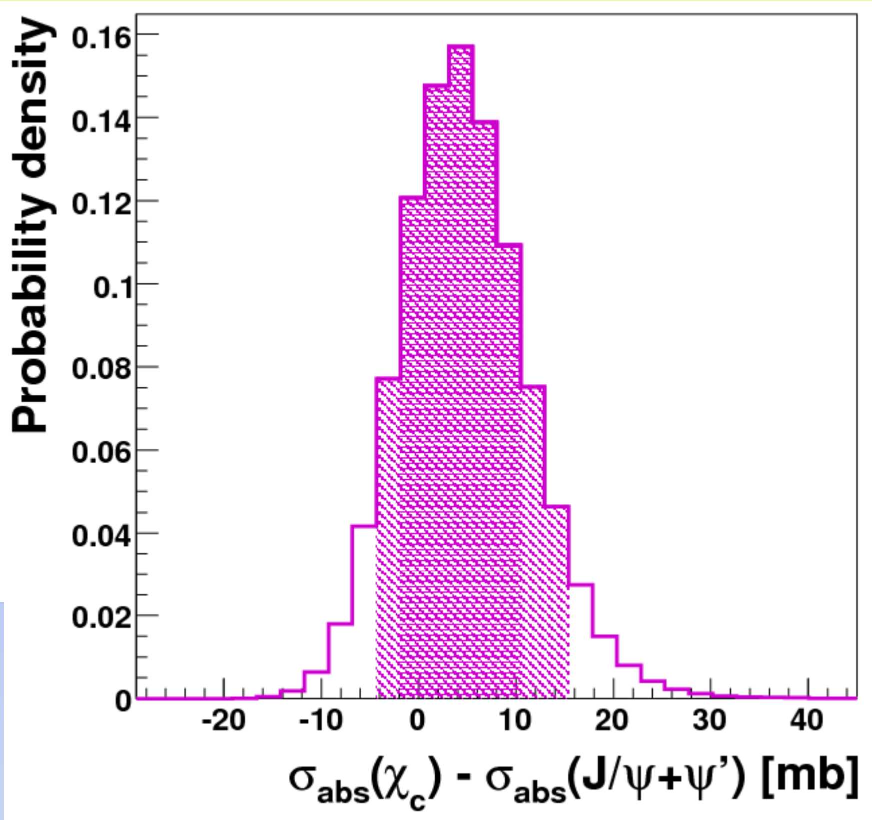
J/ψ feed-down contributions: from χ_c decays



A simple global average of all data points gives a very bad fit quality: $P(\chi^2) < 1\%$

What if we concentrate on the mid-rapidity region and allow the J/ψ and χ_c to have different absorption cross sections?





The quality of the data description improves very much: $P(\chi^2)$ = 25%

The “pp” feed-down fraction becomes

$R^0(\chi_c)$ = 25 ± 5 %

$\Delta\sigma_{abs}$ > 0 at 75% c.l.

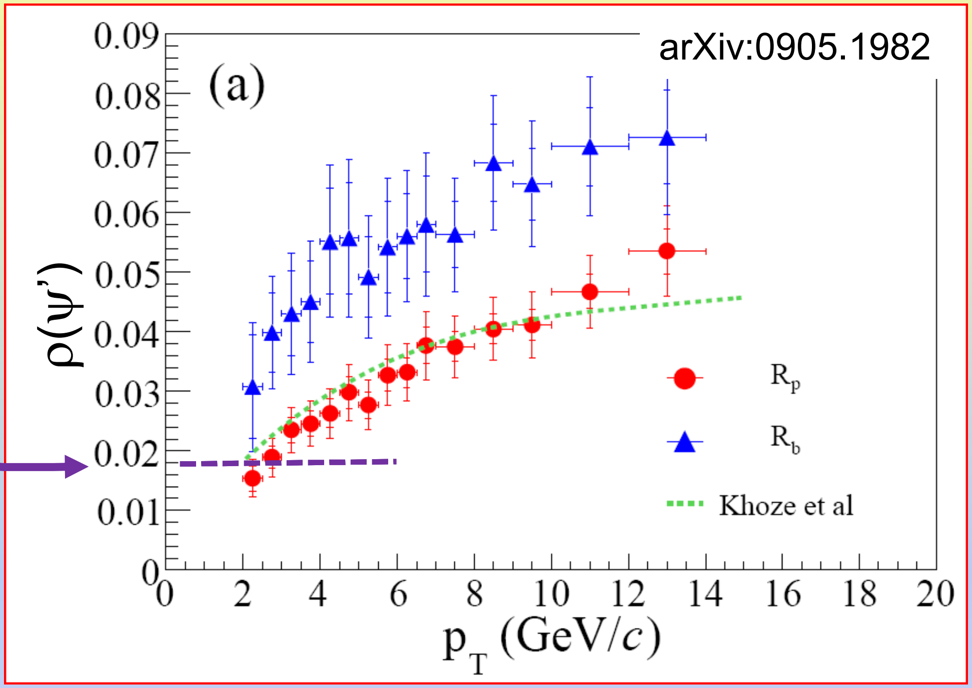
nuclear matter breaks the χ_c more easily than the J/ψ

Feed-down contributions versus transverse momentum

$$R(\psi') = \left[\frac{BR(J/\psi \to \mu\mu)}{BR(\psi' \to \mu\mu)} BR(\psi' \to J/\psi X) \right] \cdot \rho(\psi')$$

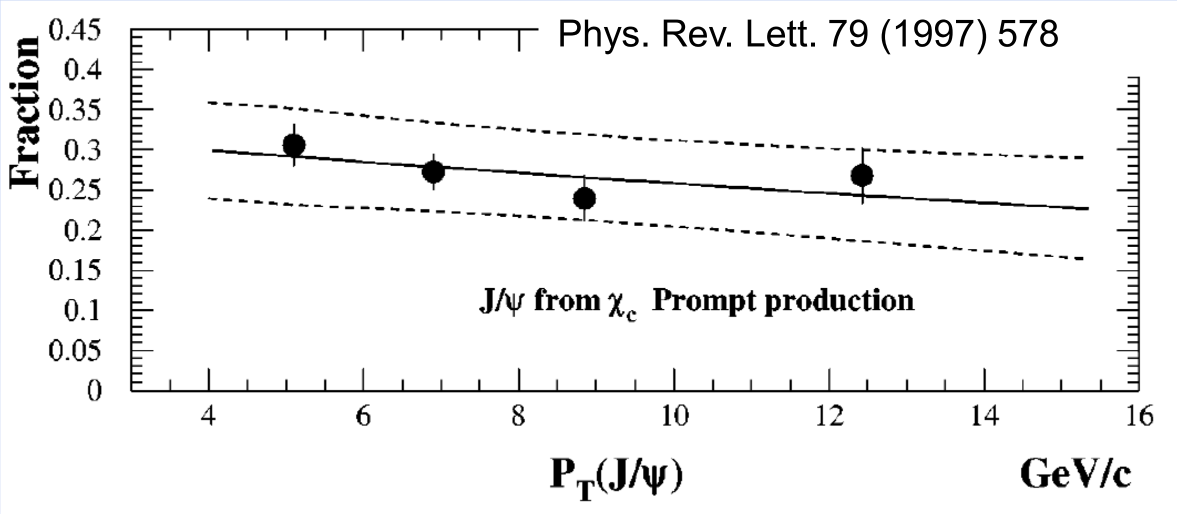
R(ψ’) = (4.53±0.13) ρ(ψ’)

ρ(ψ’) from fit to low energy data



At CDF energies (~ 2 TeV) the J/ψ feed-down fraction from ψ’ decays increases with p_T …

… while the feed-down fraction from χ_c decays seems to decrease with p_T



Summary

• There are several different “cold nuclear matter effects” affecting quarkonium production in proton-nucleus collisions

• Our best chance to disentangle them is to perform a global study of many sets of nuclear dependent measurements, including J/ψ, ψ’ and χ_c mesons, but also open charm and Drell-Yan, as a function of kinematics, collision energy, etc

• Once we have a more complete model, incorporating initial state parton energy loss, formation time effects, final state break-up, etc., we can derive “expected” absorption patterns for light-ion collisions, and calibrate the extrapolation from p-A to A-A, before addressing the more difficult, and more exciting, heavy-ion results

Additional slides

Some J/ψ data we have considered

	$B \times \sigma^{J/\psi} / A$ [nb/nucleon]		
	NA50-400	NA50-450 "LI"	NA50-450 "HI"
Be	4.717 ± 0.10	5.27 ± 0.23	5.11 ± 0.18
Al	4.417 ± 0.10	5.14 ± 0.21	4.88 ± 0.23
Cu	4.280 ± 0.09	4.97 ± 0.22	4.74 ± 0.18
Ag	3.994 ± 0.09	4.52 ± 0.20	4.45 ± 0.15
W	3.791 ± 0.08	4.17 ± 0.37	4.05 ± 0.15
Pb	3.715 ± 0.08		

NA3	
x_F range	H / Pt ratio
0.0 / 0.1	1.27 ± 0.07
0.1 / 0.2	1.40 ± 0.06
0.2 / 0.3	1.34 ± 0.07
0.3 / 0.4	1.36 ± 0.12
0.4 / 0.5	1.75 ± 0.22
0.5 / 0.6	2.62 ± 0.52
0.6 / 0.7	3.58 ± 1.81

E866		
x_F range	$\langle x_F \rangle$	W / Be ratio
−0.10 / −0.05	−0.0652	0.8929 ± 0.0184
−0.05 / 0.00	−0.0188	0.8682 ± 0.0084
0.00 / +0.05	+0.0269	0.8720 ± 0.0060
+0.05 / +0.10	+0.0747	0.8739 ± 0.0057
+0.10 / +0.15	+0.1235	0.8652 ± 0.0067
+0.15 / +0.20	+0.1729	0.8725 ± 0.0100

HERA-B		
x_F range	$\langle x_F \rangle$	W / C ratio
−0.34 / −0.26	−0.285	1.105 ± 0.158
−0.26 / −0.22	−0.237	1.034 ± 0.096
−0.22 / −0.18	−0.197	1.090 ± 0.063
−0.18 / −0.14	−0.158	1.043 ± 0.042
−0.14 / −0.10	−0.118	0.986 ± 0.030
−0.10 / −0.06	−0.079	0.943 ± 0.022
−0.06 / −0.02	−0.040	0.915 ± 0.021
−0.02 / +0.02	−0.002	0.916 ± 0.025
+0.02 / +0.06	+0.037	0.902 ± 0.036
+0.06 / +0.14	+0.075	0.866 ± 0.063

J/ψ σ_{abs} for each kinematical window and nPDF set

Exp.	x_F	$\sigma_{abs}^{J/\psi}$ [mb] NONE	nDS	nDSg	EKS98	EPS08
NA3	0.05	3.77 ± 0.98	3.94 ± 0.99	4.27 ± 1.00	5.79 ± 1.07	7.00 ± 1.12
	0.15	5.35 ± 0.88	5.46 ± 0.88	5.85 ± 0.89	7.38 ± 0.95	8.15 ± 0.98
	0.25	4.66 ± 0.98	4.63 ± 0.98	5.01 ± 0.99	6.18 ± 1.04	6.38 ± 1.05
	0.35	$4.96^{+1.51}_{-1.56}$	$4.71^{+1.49}_{-1.54}$	$5.07^{+1.51}_{-1.56}$	$5.81^{+1.56}_{-1.61}$	$5.62^{+1.55}_{-1.60}$
NA50-400		$\boxed{4.83 \pm 0.63}$	4.74 ± 0.62	4.73 ± 0.62	$\boxed{7.01 \pm 0.70}$	7.98 ± 0.74
450-LI		4.51 ± 1.58	4.39 ± 1.58	4.39 ± 1.58	6.89 ± 1.76	7.93 ± 1.83
450-HI		4.82 ± 1.10	4.71 ± 1.09	4.71 ± 1.09	7.17 ± 1.22	8.21 ± 1.28
E866	-0.0652	$2.37^{+0.83}_{-0.77}$	$2.32^{+0.83}_{-0.77}$	$3.01^{+0.85}_{-0.79}$	$4.67^{+0.92}_{-0.85}$	$6.06^{+0.98}_{-0.90}$
	-0.0188	$3.00^{+0.73}_{-0.69}$	$2.85^{+0.73}_{-0.69}$	$3.62^{+0.75}_{-0.71}$	$5.39^{+0.82}_{-0.76}$	$6.20^{+0.85}_{-0.79}$
	$+0.0269$	$2.90^{+0.71}_{-0.67}$	$2.65^{+0.70}_{-0.66}$	$3.27^{+0.72}_{-0.68}$	$4.98^{+0.78}_{-0.73}$	$5.03^{+0.78}_{-0.73}$
	$+0.0747$	$2.85^{+0.71}_{-0.67}$	$2.50^{+0.70}_{-0.66}$	$2.65^{+0.70}_{-0.66}$	$4.36^{+0.76}_{-0.71}$	$3.81^{+0.74}_{-0.70}$
	$+0.1235$	$3.07^{+0.72}_{-0.68}$	$2.61^{+0.71}_{-0.67}$	$2.13^{+0.69}_{-0.65}$	$3.95^{+0.75}_{-0.71}$	$2.98^{+0.72}_{-0.68}$
	$+0.1729$	$2.89^{+0.74}_{-0.70}$	$2.31^{+0.73}_{-0.68}$	$1.28^{+0.69}_{-0.65}$	$3.13^{+0.75}_{-0.71}$	$1.91^{+0.71}_{-0.67}$
HERA-B	-0.158	—	—	—	$0.73^{+1.42}_{-0.73}$	$2.23^{+1.52}_{-1.35}$
	-0.118	$0.34^{+1.22}_{-0.34}$	$0.42^{+1.22}_{-0.42}$	$0.96^{+1.25}_{-0.96}$	$2.34^{+1.33}_{-1.20}$	$3.88^{+1.43}_{-1.28}$
	-0.079	$1.39^{+1.18}_{-1.08}$	$1.38^{+1.18}_{-1.08}$	$2.04^{+1.22}_{-1.11}$	$3.68^{+1.32}_{-1.19}$	$5.08^{+1.41}_{-1.26}$
	-0.040	$2.11^{+1.21}_{-1.10}$	$1.99^{+1.20}_{-1.09}$	$2.76^{+1.24}_{-1.13}$	$4.53^{+1.36}_{-1.22}$	$5.46^{+1.42}_{-1.27}$
	-0.002	$2.10^{+1.28}_{-1.15}$	$1.85^{+1.26}_{-1.14}$	$2.58^{+1.31}_{-1.18}$	$4.32^{+1.42}_{-1.27}$	$4.58^{+1.44}_{-1.29}$
	$+0.037$	$2.46^{+1.51}_{-1.34}$	$2.09^{+1.49}_{-1.32}$	$2.51^{+1.52}_{-1.35}$	$4.28^{+1.65}_{-1.45}$	$3.94^{+1.63}_{-1.43}$
	$+0.075$	$3.52^{+2.43}_{-2.02}$	$2.96^{+2.36}_{-1.97}$	$2.52^{+2.31}_{-1.93}$	$4.58^{+2.56}_{-2.11}$	$3.59^{+2.44}_{-2.02}$

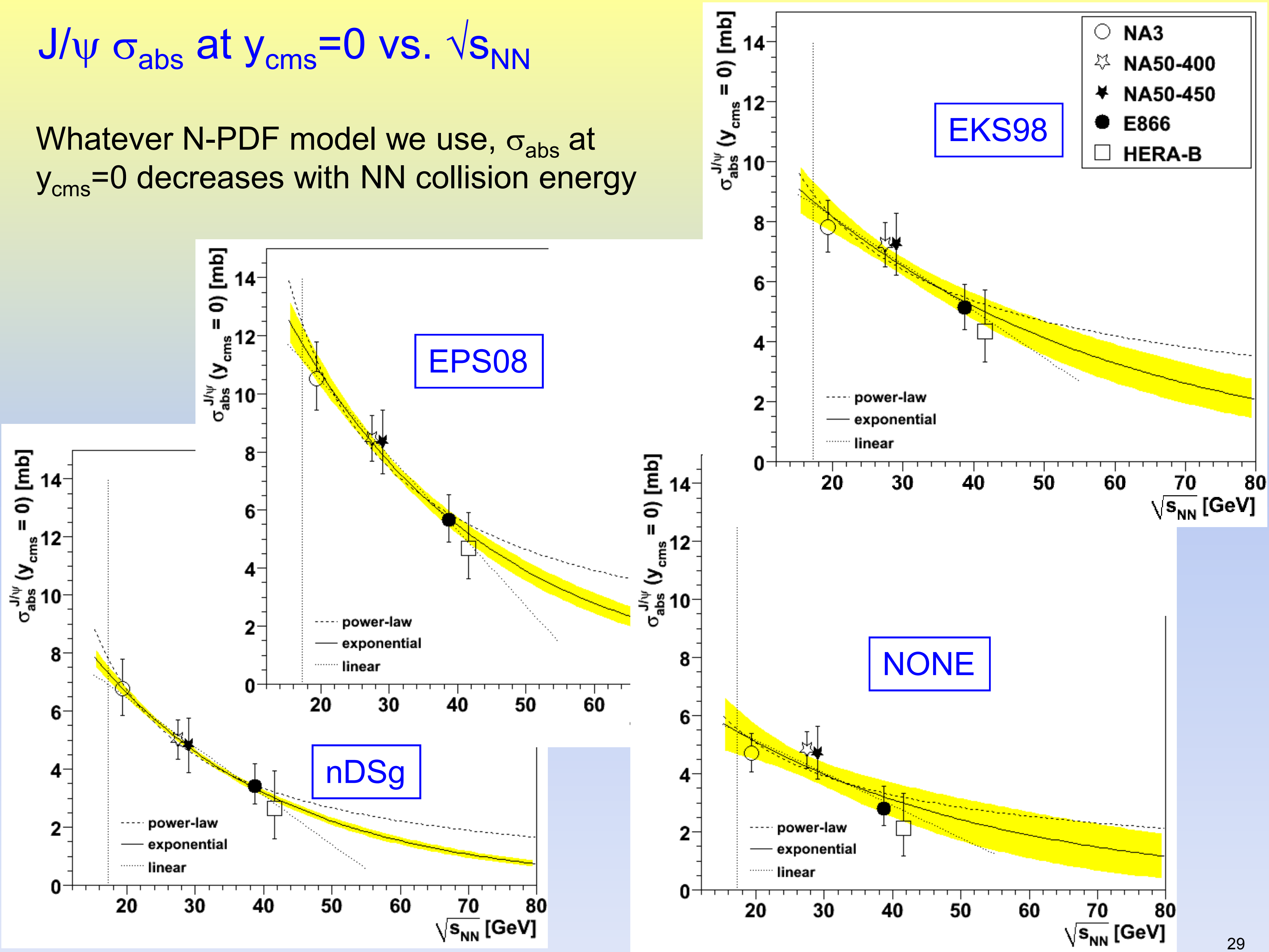
Errors include the global systematic uncertainties of the ratios:

3% in NA3
3% in E866
4% in HERA-B

C. Lourenço, R. Vogt and H.K. Wöhri, JHEP 2 (09) 14

J/ψ σ_{abs} at y_{cms}=0 vs. $\sqrt{s_{NN}}$

Whatever N-PDF model we use, σ_{abs} at y_{cms}=0 decreases with NN collision energy



Initial state energy loss: E866